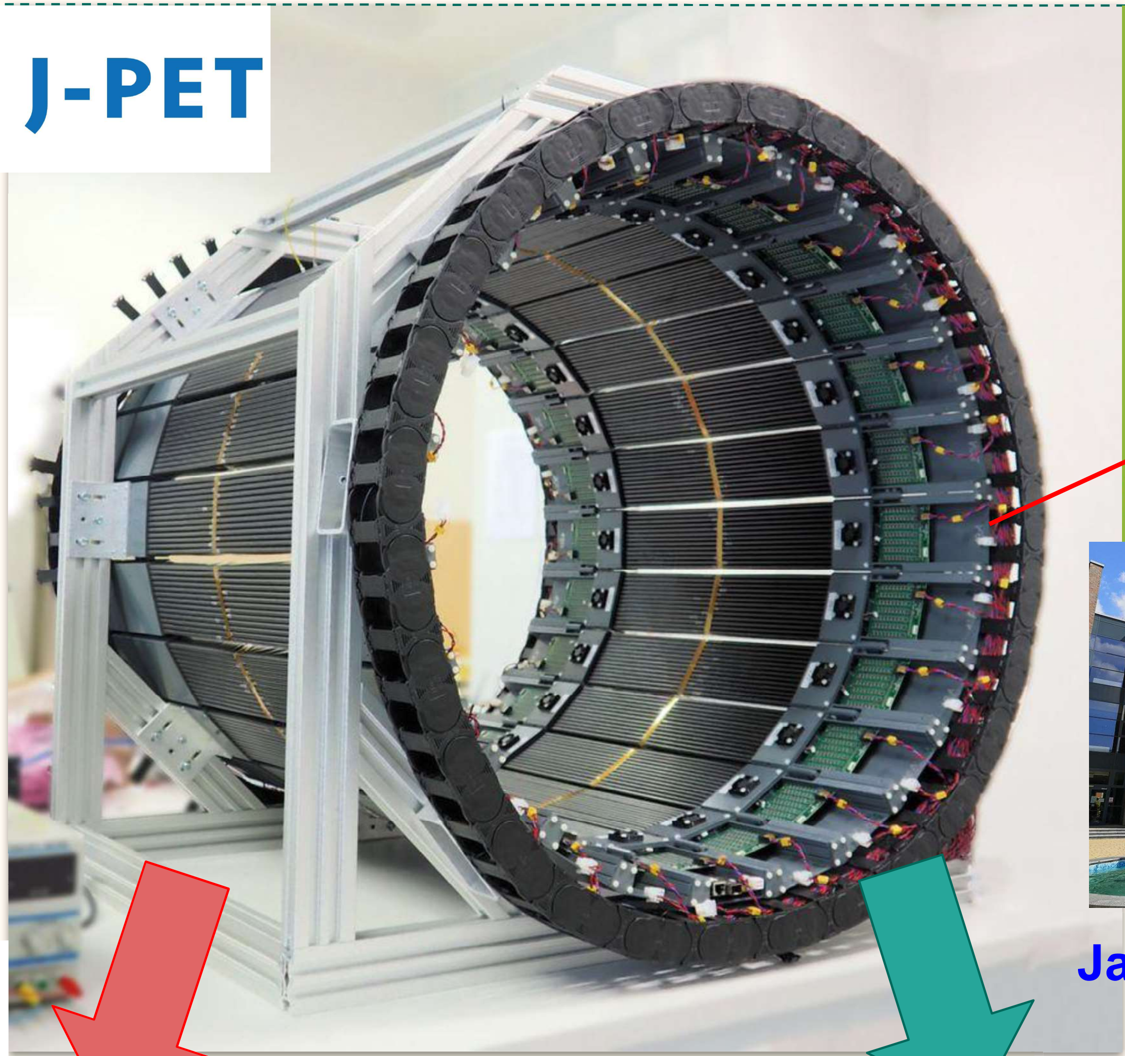
The J-PET tomograph as an advanced, multifunctional detection system for applications in medical imaging and fundamental research

Magdalena Skurzok
on behalf of the **J-PET** Collaboration

HPXM Workshop
Frascati, 16-20.06.2025

J-PET tomograph - multidisciplinary detection system

J-PET

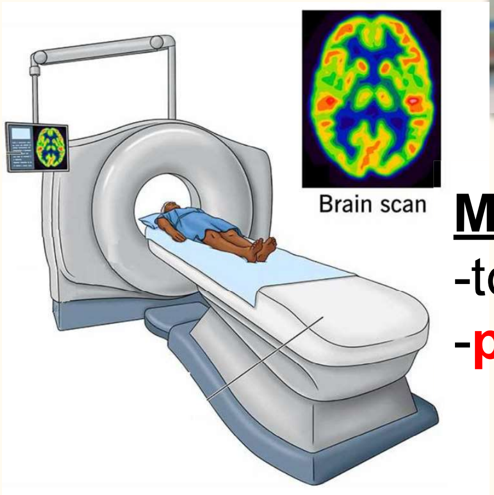


Plastic scintillators

Cost effective

Multiphoton detector

Jagiellonian University Krakow



Medical imaging:

-total body PET

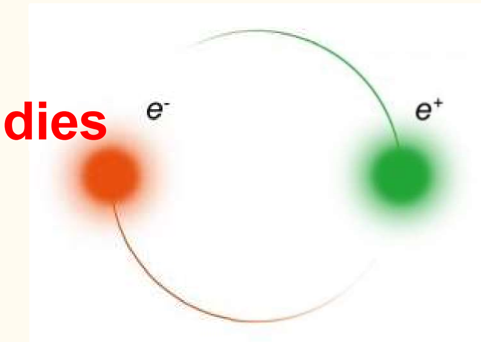
-**positronium imaging**

Fundamental studies:

-**discrete symmetry studies**

-quantum entanglement

-mirror matter studies



J-PET tomograph - multidisciplinary detection system

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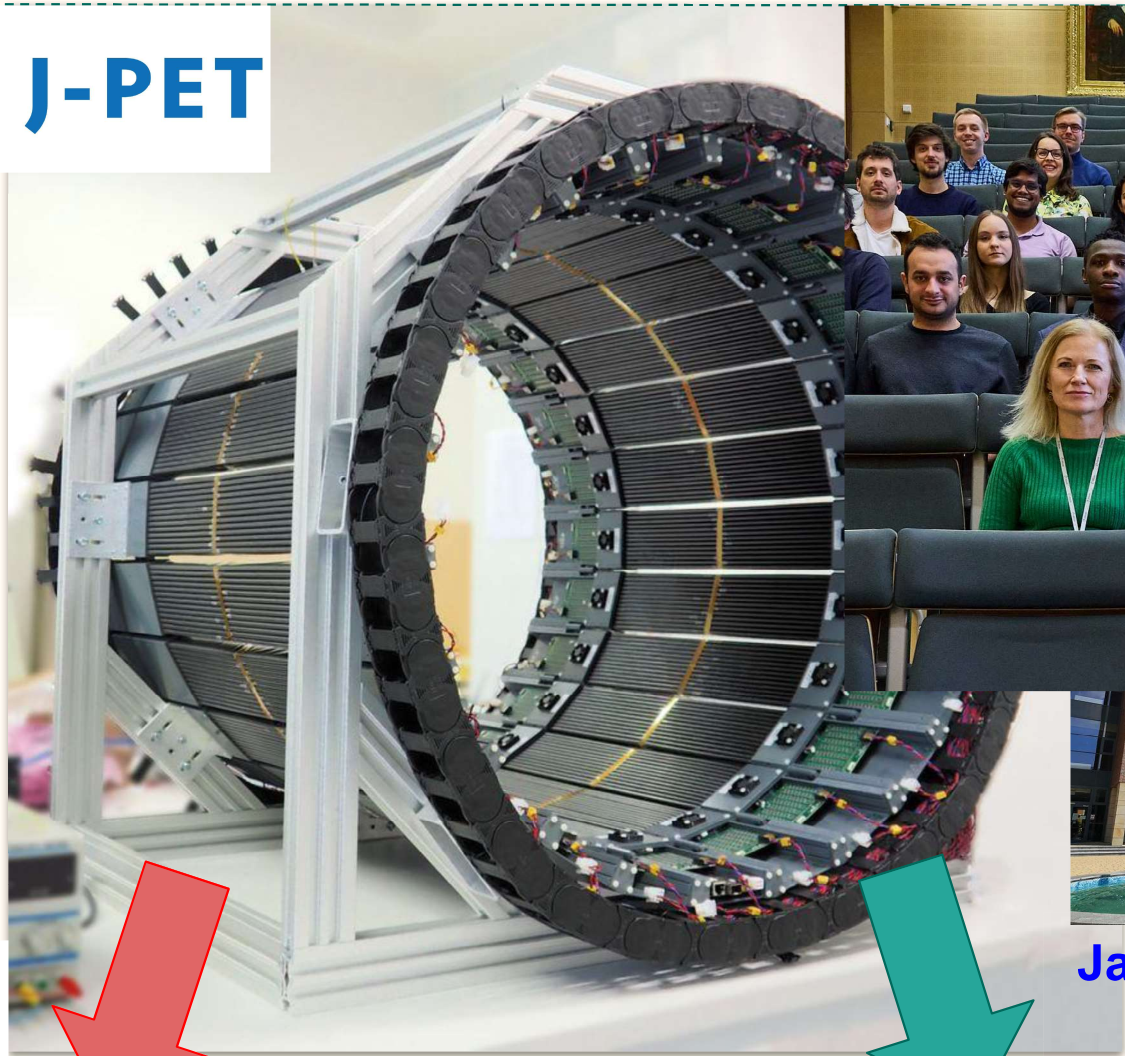
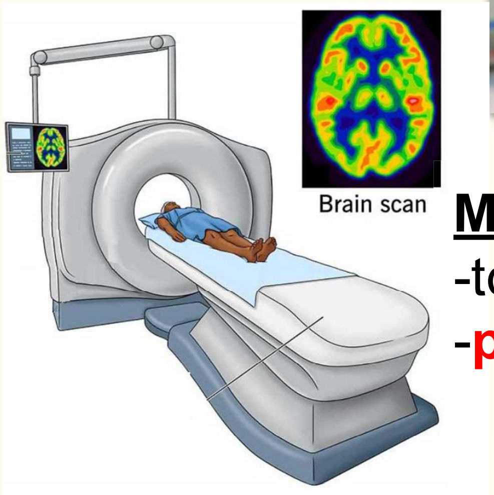


Jagiellonian University Krakow



<u>Medical imaging:</u>
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<u>Fundamental studies:</u>
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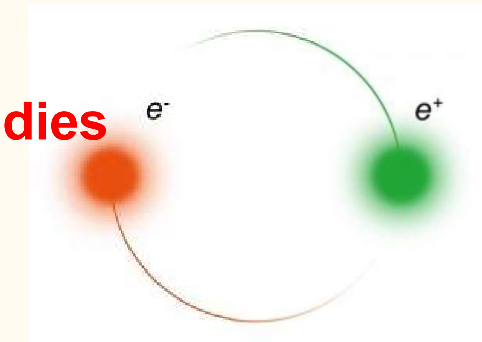
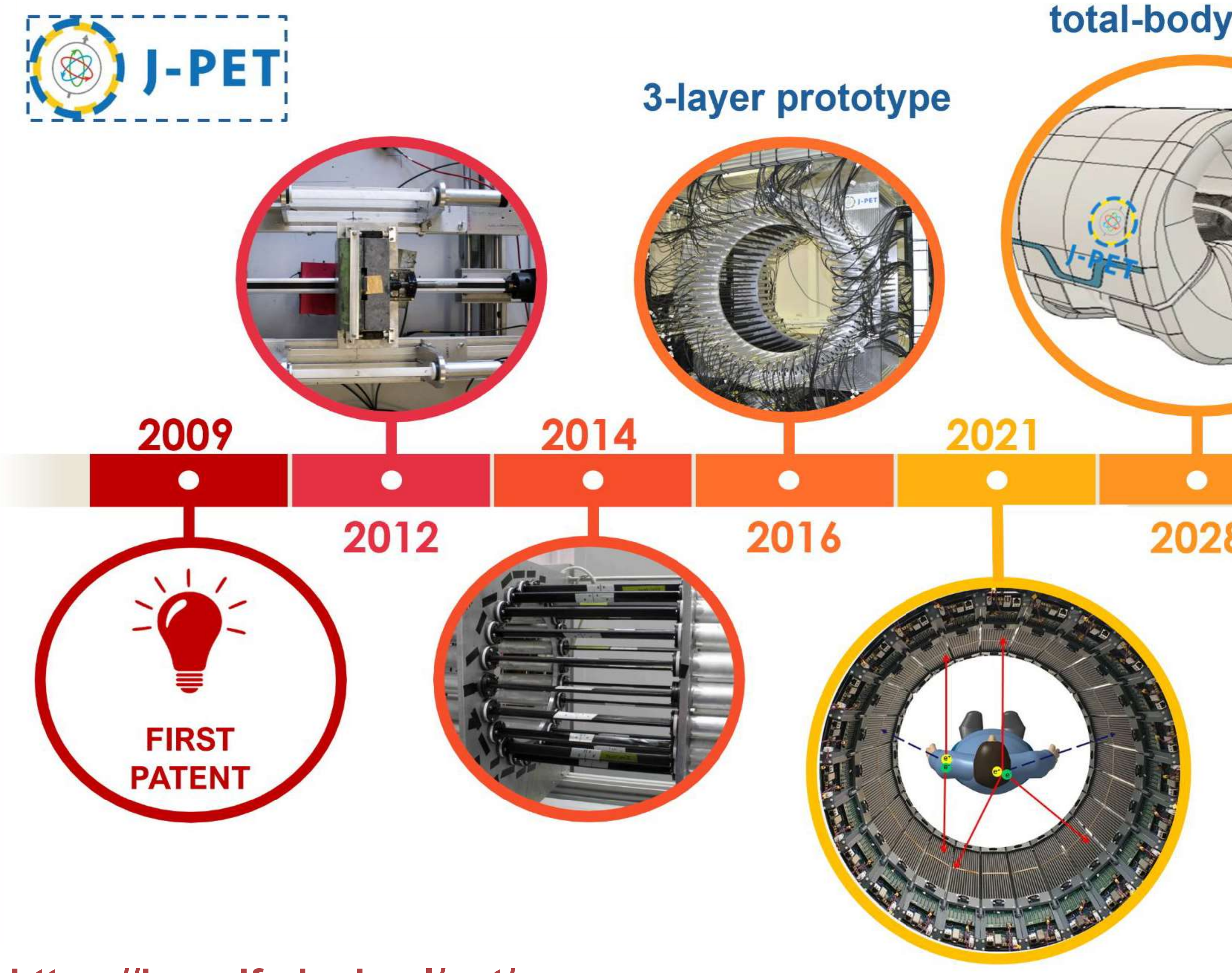
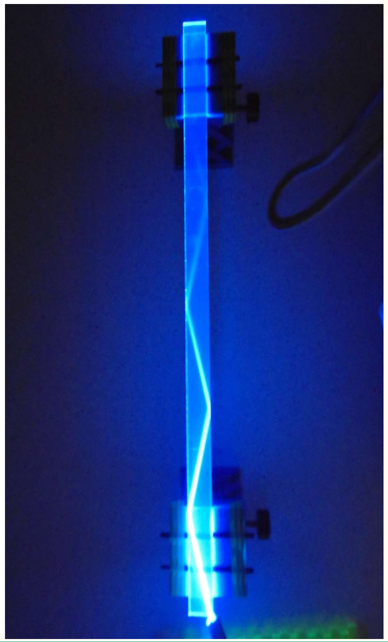
- quantum entanglement
- mirror matter studies



J-PET tomograph development at Jagiellonian University in Kraków, Poland

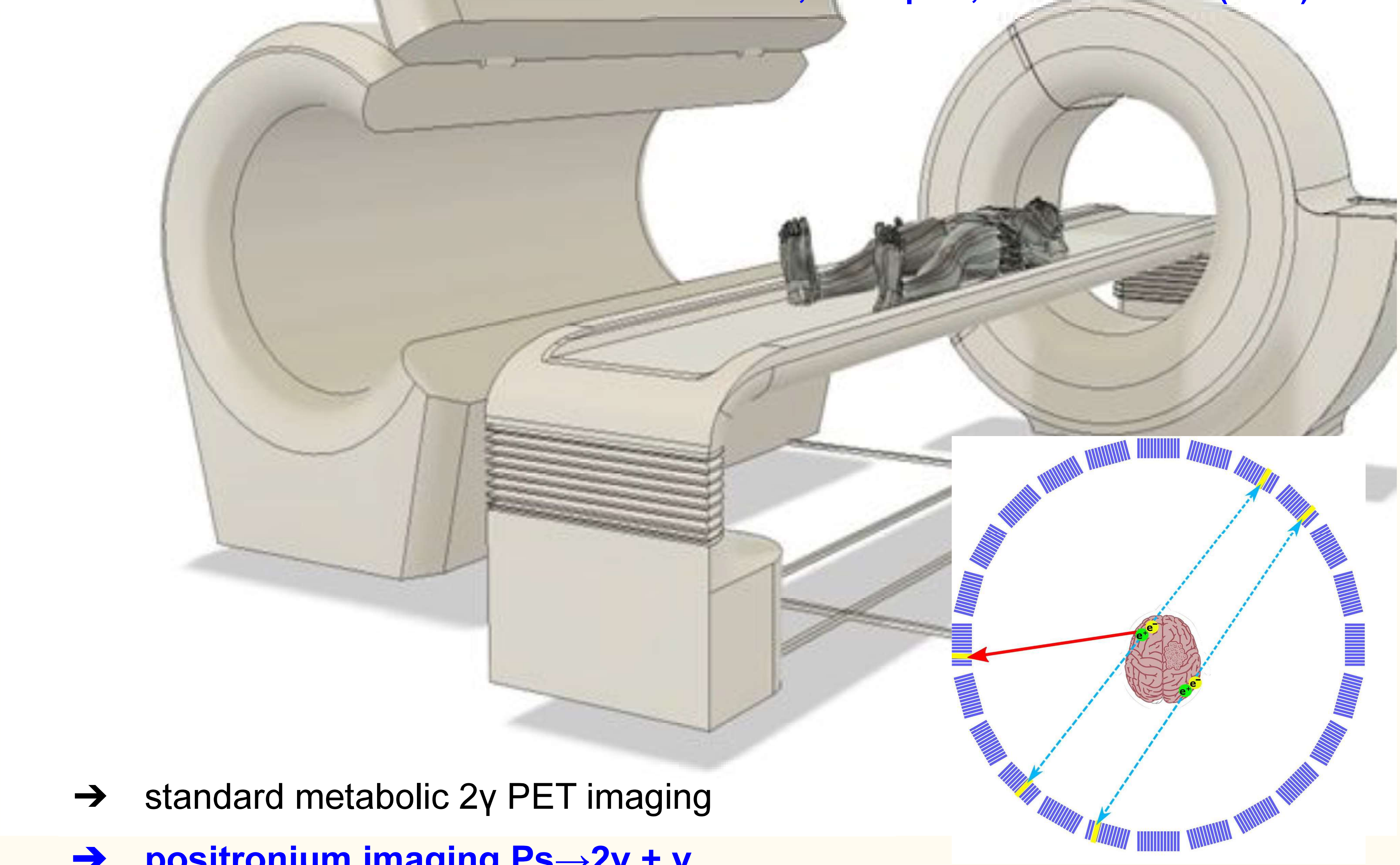




https://koza.if.uj.edu.pl/pet/
P. Moskal, E. Stepien, PET Clinics 15 (2020) 439

TB-J-PET tomograph development at JU in Kraków, Poland

P. Moskal, E. Stepien, PET Clinics 15 (2020) 439

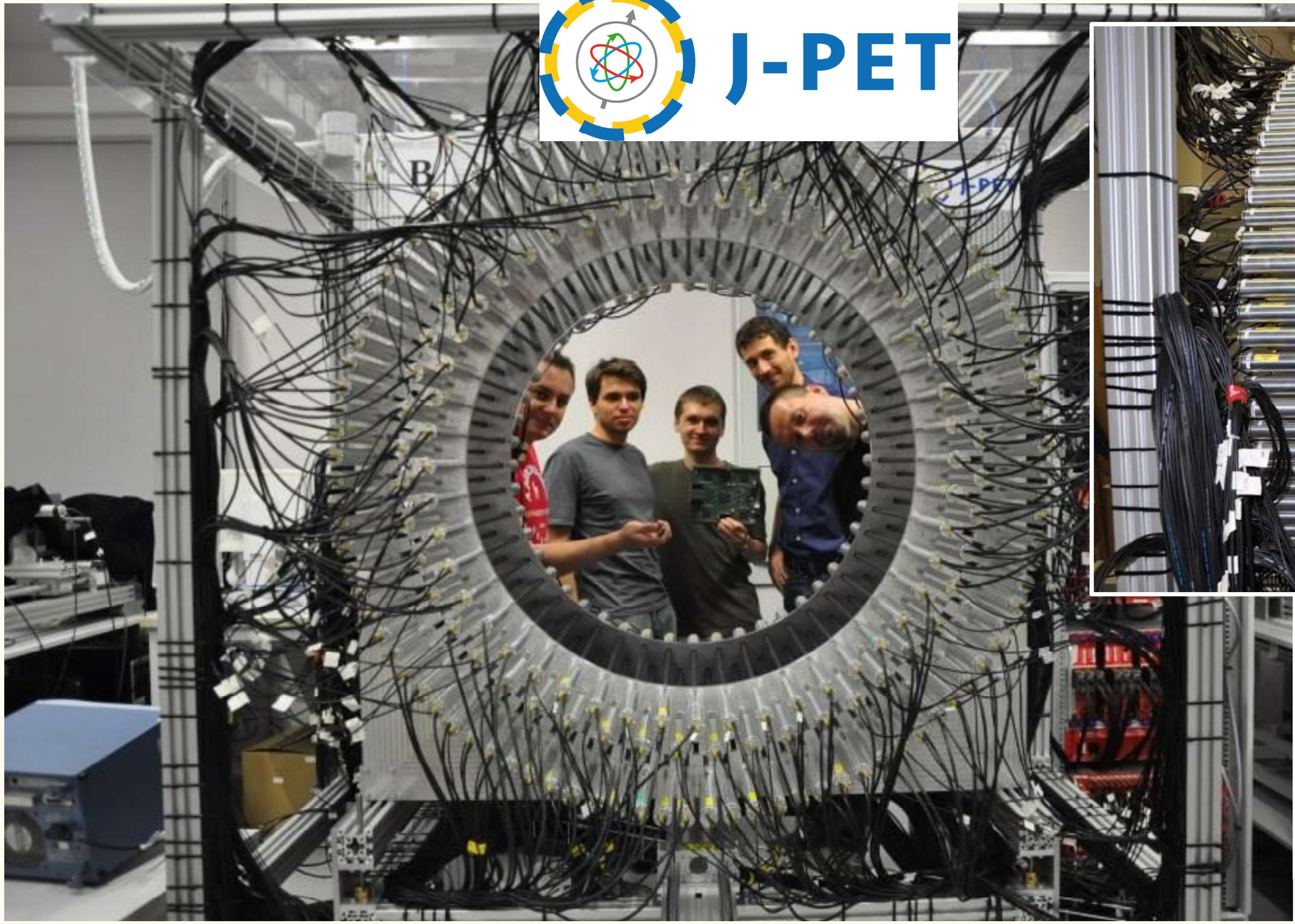


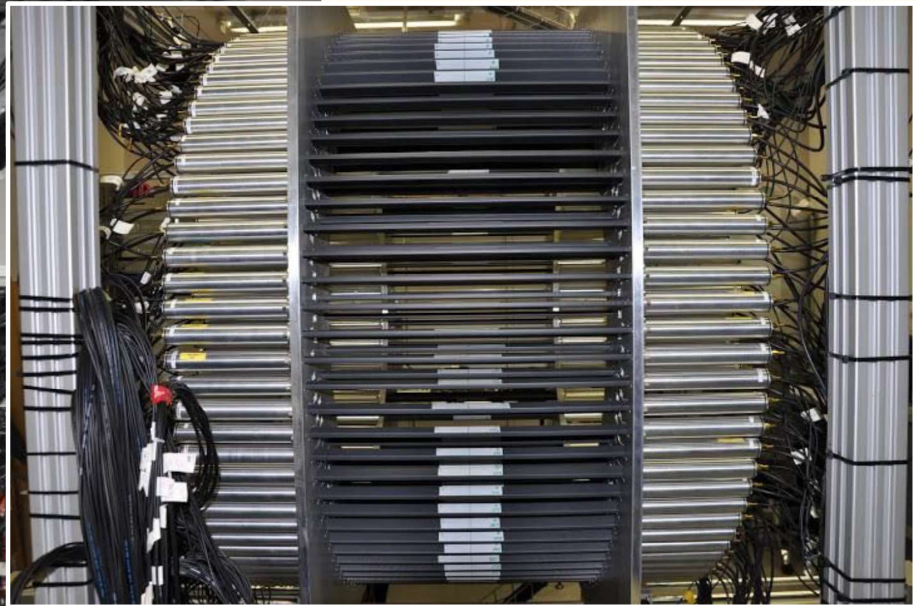
- ➔ standard metabolic 2γ PET imaging
- ➔ **positronium imaging $Ps \rightarrow 2\gamma + \gamma_{prompt}$**

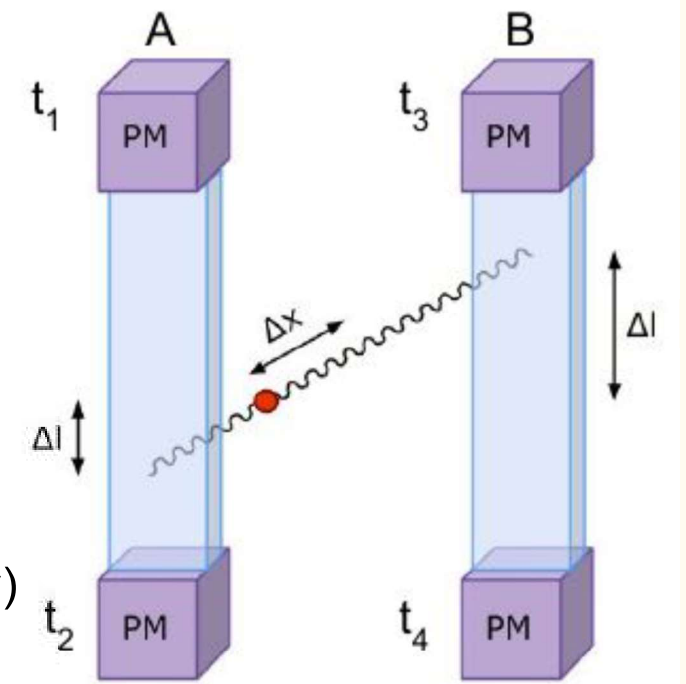
Ministy of Science and Higher Education Grant: IAL/SP/596235/2023

➔

J-PET 3 layer detector at Jagiellonian University in Kraków, Poland



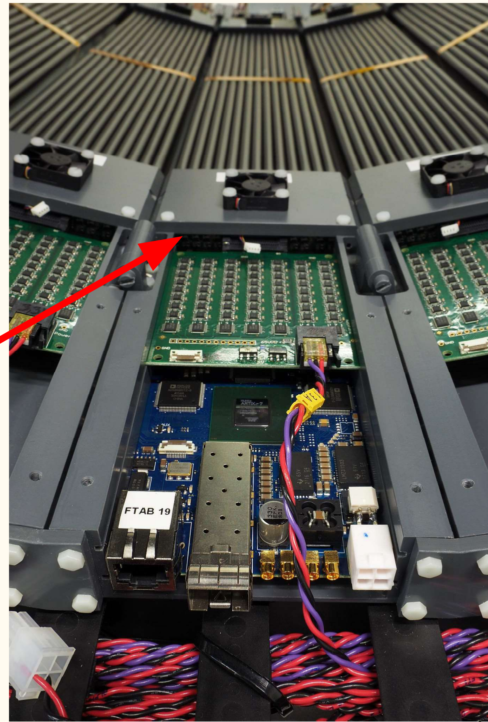


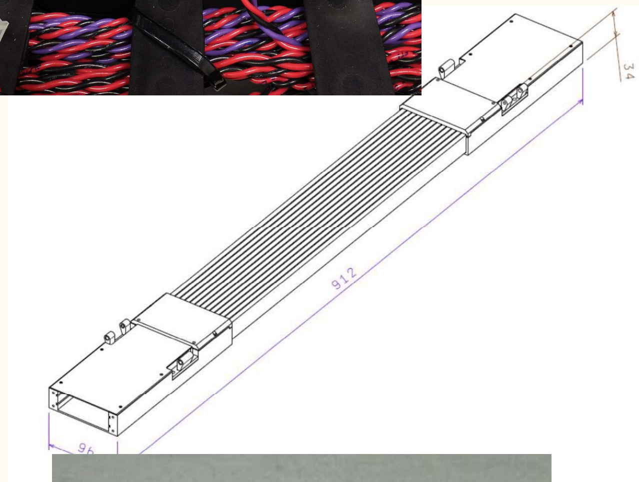


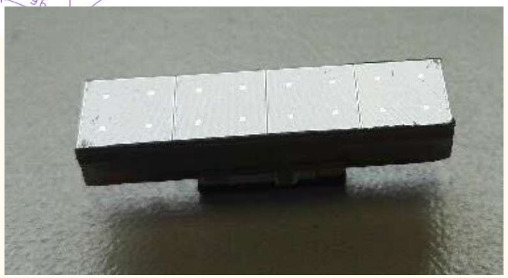
- 3 layers,192 EJ-230 scintillators: 7x19x500 mm^3
- 85 cm radius, 384 R9800 photomultipliers,1536 channels
- plastic scintillators - small light attenuation, large transparency
- dedicated multithreshold digital electronics (30ps time accuracy) and the novel trigger-less DAQ
- interaction time resolution ~250ps, angular resolution ~ 1deg

[P. Moskal et al., Acta Phys. Polon. B47 (2016) 509; G. Korcyl, et al., IEEE Trans. Med. Imag. 37, 2526 (2018)]

J-PET modular detector at Jagiellonian University in Kraków, Poland







- modular design: 24 modules - each 13 strips (in total 312 strips)
- 74 cm diameter, 50 cm FOV, 4 SiPM per scintillator side
- plastic scintillators - small light attenuation
- 2 constant threshold per SiPM, trigger-less DAQ
- digital data at the module output
- interaction time resolution ~250ps, angular resolution ~ 0.4deg

[P. Moskal et al., Acta Phys. Polon. B47 (2016) 509; G. Korcyl, et al., IEEE Trans. Med. Imag. 37, 2526 (2018)]

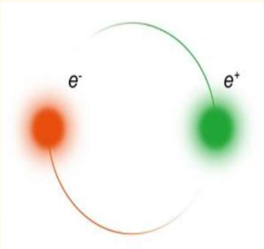
POSITRONIUM

the lightest purely leptonic object

bound by a central potential

$\Downarrow$

is eigenstate of the parity operator P



symmetric under the exchange of particles - anti-particles

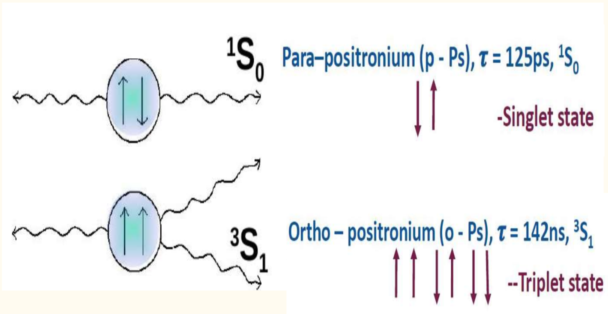
$\Downarrow$

is eigenstate of the charge conjugation operator C

$P|Ps>=(-1)^L|Ps>$

$C|Ps>=(-1)^{L+S}|Ps>$

eigenstate of the CP operator



even number of photons

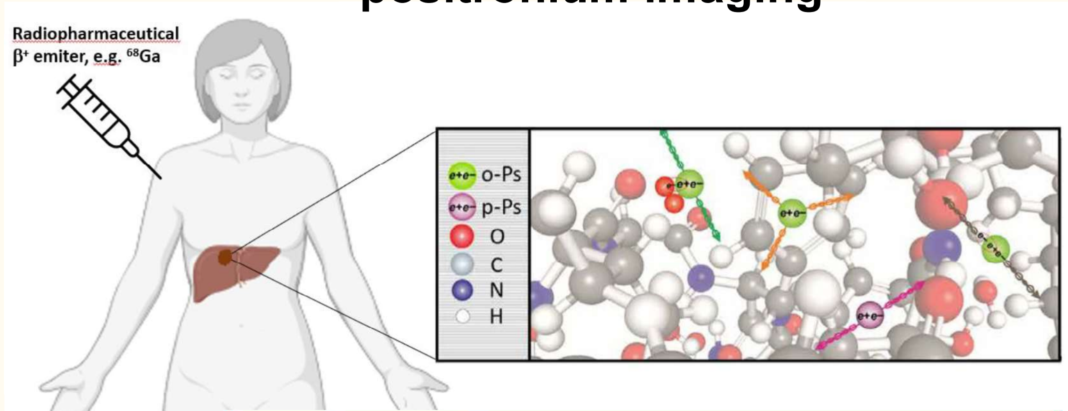
symm. of charge conjugation C

odd number of photons

Ps state	τ [ns]	L	S	J	J_z	P	C	CP
$^1S_0$ (para-Ps)	0.125	0	0	0	0	-	+	-
$^3S_1$(ortho-Ps)	142	0	1	1	-1,0,1	-	-	+

experiments with Ps - CP, T or CPT violation excluded at the level of about 0.3% - many orders of magnitude less precise than the accuracies achieved in the quark sector

positronium imaging



$$1/\tau_0^{p(o)} = \lambda_0^{p(o)} + \lambda_{\text{pickoff}}(t) + \lambda_{\text{conv}}(C) + \lambda_{\text{other}}(C)$$

p-Ps annihilation to 2γ **o-Ps decay to 3γ**

pick-off process -> 2γ

o-Ps to p-Ps conversion followed by 2γ decay

The volume of free spaces ↗ ⇒ o-Ps lifetime ↗

3γ fraction ↗ 2γ fraction ↘

The volume of free spaces ↘ ⇒ o-Ps lifetime ↘

3γ fraction ↘ 2γ fraction ↗

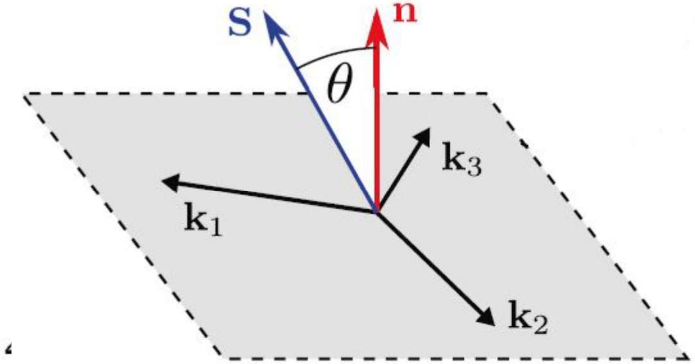
o-Ps lifetime and 3γ/2γ annihilation ratio ⇒ diagnostic indicator in PET imaging assessment of tissue pathology in-vivo at the molecular level, and thus the determination of the grade of cancer malignancy without performing biopsy ->virtual biopsy

P. Moskal, E. Stepien, PET Clinics 15 (2020) 439

Testing discrete symmetries with angular correlations in o-Ps→3γ decays

Measurement the expectation value of the symmetry odd-operators

$$e^+e^- \to \text{o-Ps} \to 3\gamma$$



$$\langle \hat{O} \rangle \stackrel{?}{=} 0 \quad \text{for an odd operator}$$

$$\Leftrightarrow \mathcal{CPT}(\hat{O}) = -1$$

$$\Leftrightarrow \mathcal{T}(\hat{O}) = -1$$

$$|\vec{k}_1| > |\vec{k}_2| > |\vec{k}_3|$$

Required:

- the o-Ps spin determination
- of o-Ps→3γ decays selection

(determination of photons momenta)

- determination of annihilation γ polarization

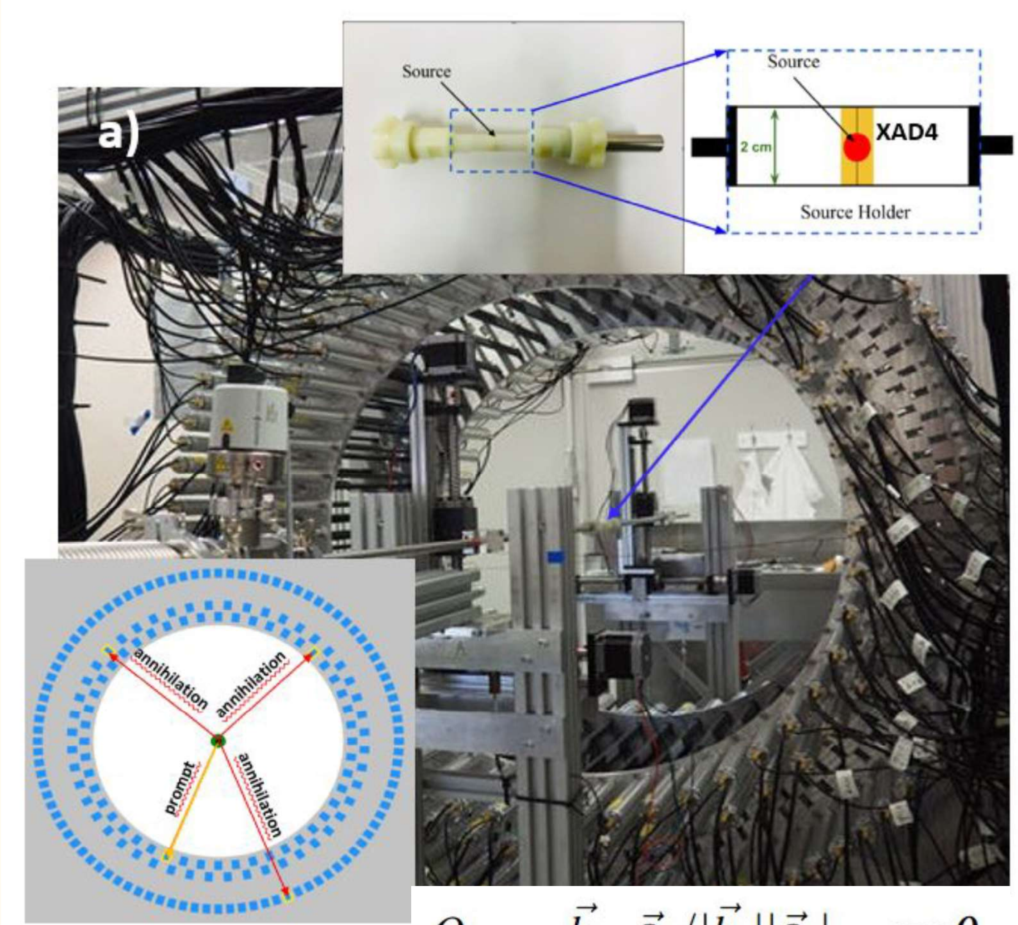
$$O_{CPT} = \vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)/|\vec{k}_1 \times \vec{k}_2| = cos\theta$$

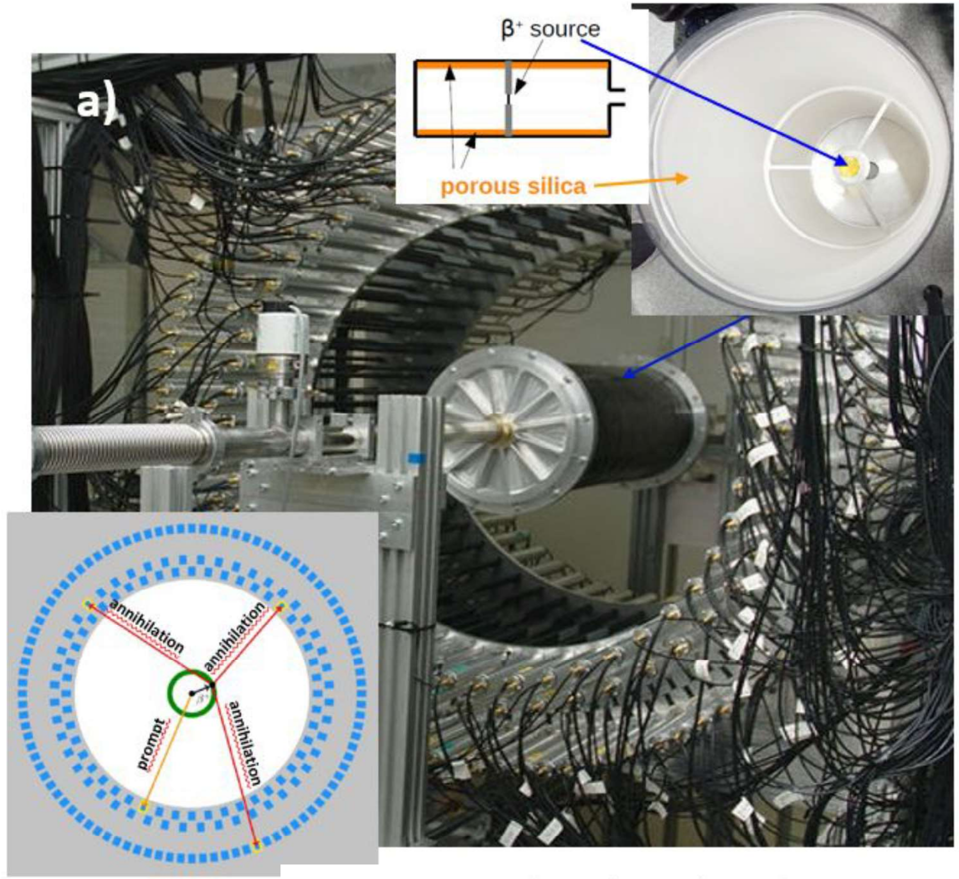
$$O_{CP} = \vec{k}_1 \cdot \vec{\varepsilon}_2/|\vec{k}_1||\vec{\varepsilon}_2| = cos\theta$$

Operator	C	P	T	CP	CPT
$\vec{S} \cdot \vec{k}_1$	+	-	+	-	-
$\boxed{\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2)}$	+	+	-	+	$\boxed{-}$
$(\vec{S} \cdot \vec{k}_1)(\vec{S} \cdot (\vec{k}_1 \times \vec{k}_2))$	+	-	-	-	+
$\boxed{\vec{k}_1 \cdot \vec{\varepsilon}_2}$	+	-	-	$\boxed{-}$	+
$\vec{S} \cdot \vec{\varepsilon}_1$	+	+	-	+	-
$\vec{S} \cdot (\vec{k}_2 \times \vec{\varepsilon}_1)$	+	-	+	-	-

[P. Moskal et al., Acta Phys. Polon. B47 (2016) 509]

o-Ps production in J-PET with an annihilation chamber





$$O_{CP} = \vec{k}_1 \cdot \vec{\varepsilon}_2 / |\vec{k}_1||\vec{\varepsilon}_2| = cos\theta$$

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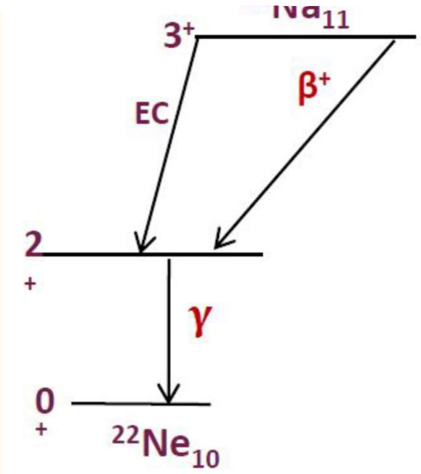
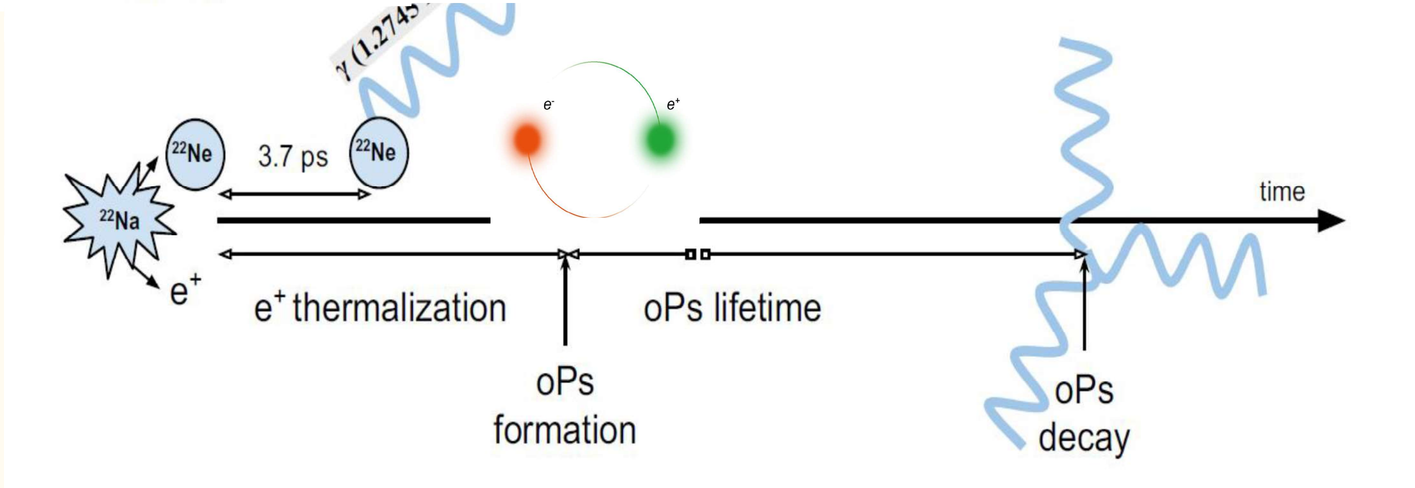
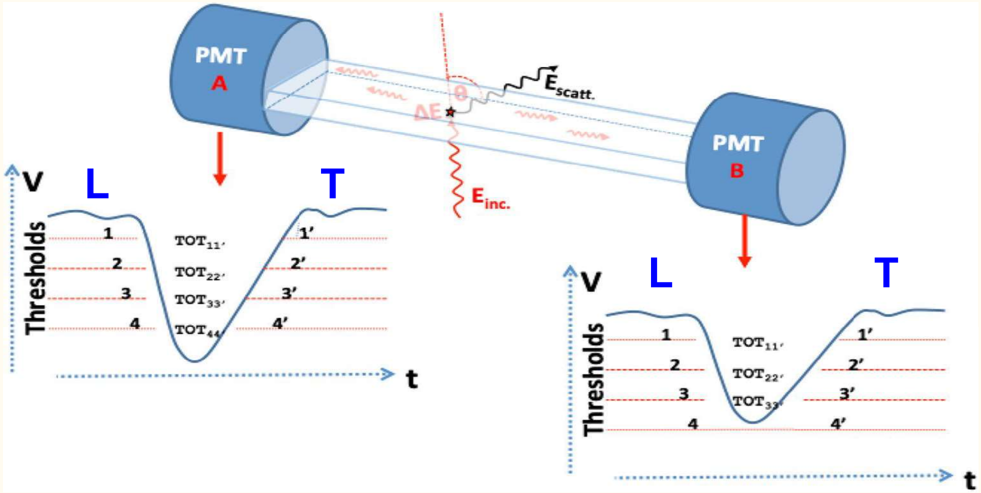
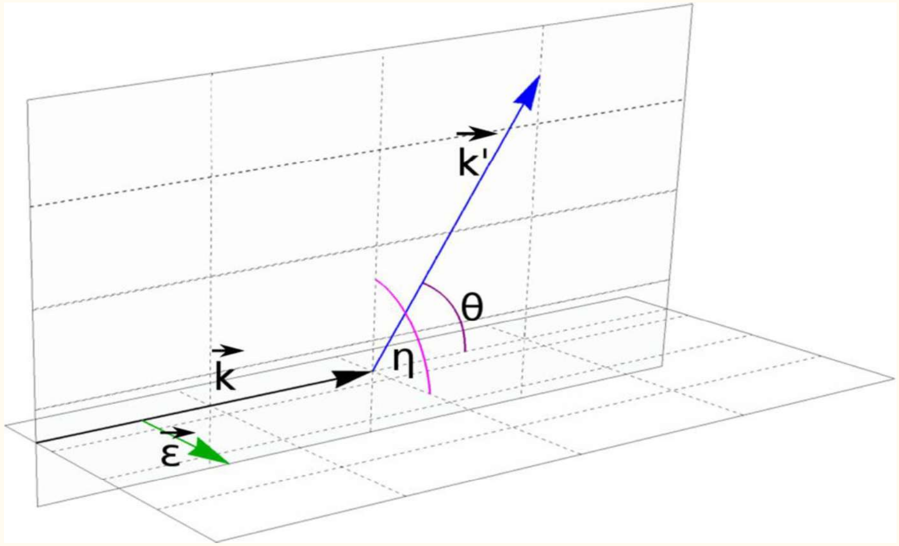




TOT as a measure of energy | determination of γ polarization in J-PET





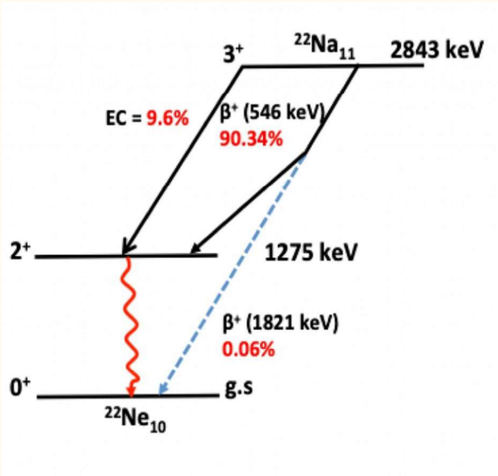
Time Over Threshold (TOT) of PMT signals from a scintillator strip corresponds to ɣ deposited energy

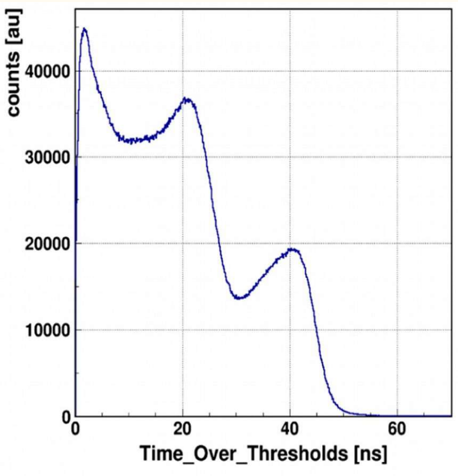
Compton scattering is at most likely in the plane perpendicular to the electric vector of the photon

direction of its linear polarization

$$\vec{\varepsilon} = \vec{k} \times \vec{k}'$$

independently of the value of theta the **probability of the scattering has its maximum** value when the **scattering plane is perpendicular to the direction of the electric vector of the primary photon**





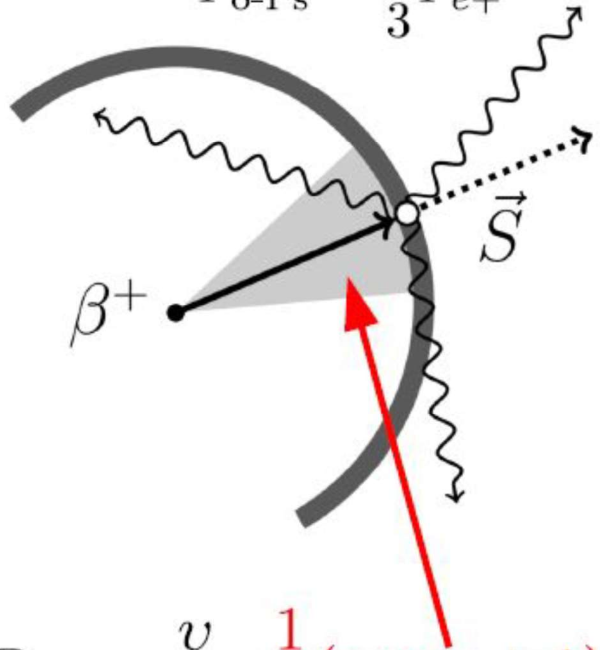
[S. Sharma, eta al., EJNMMI Phys. 7, 39 (2020)
S. Sharma, eta al., EJNMMI Phys. 10(28) (2023)]

o-Ps spin determination and o-Ps→3γ decays reconstruction in J-PET

<u>o-Ps spin estimation:</u>

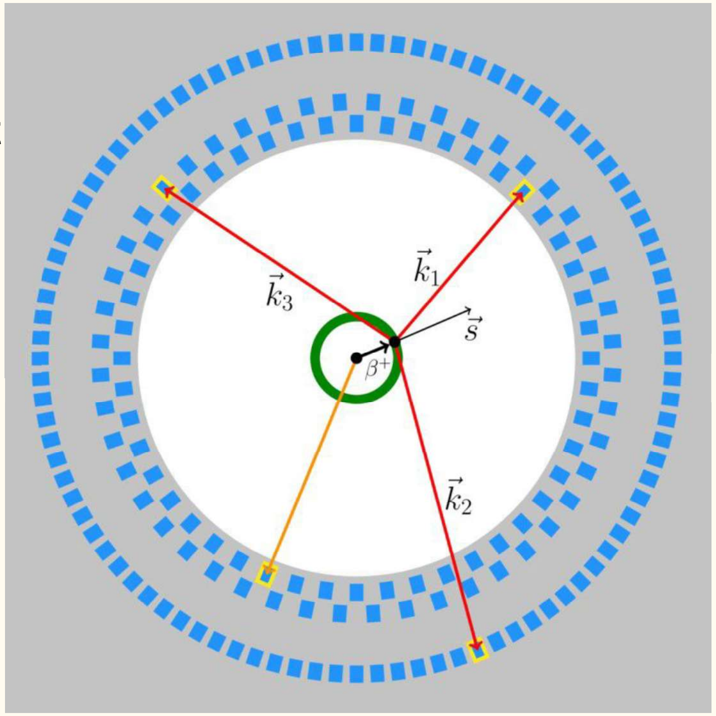
✶ e^+ spin estimated event-by-event recording multiple geometrical configurations
✶ effective polarization depends on o-Ps→3γ vertex resolution

$$P_{\text{o-Ps}} = \frac{2}{3} P_{e+}$$



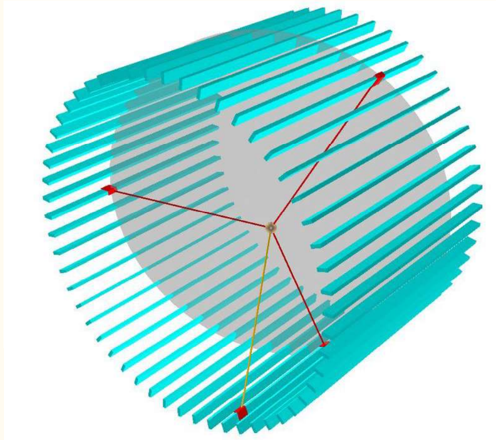
$$P_{e+} \approx \frac{v}{c} \cdot \frac{1}{2}(\cos\alpha + 1)$$

$$P_{e+} = (N^{e+}_{+1/2} - N^{e+}_{-1/2}) / (N^{e+}_{+1/2} + N^{e+}_{-1/2})$$



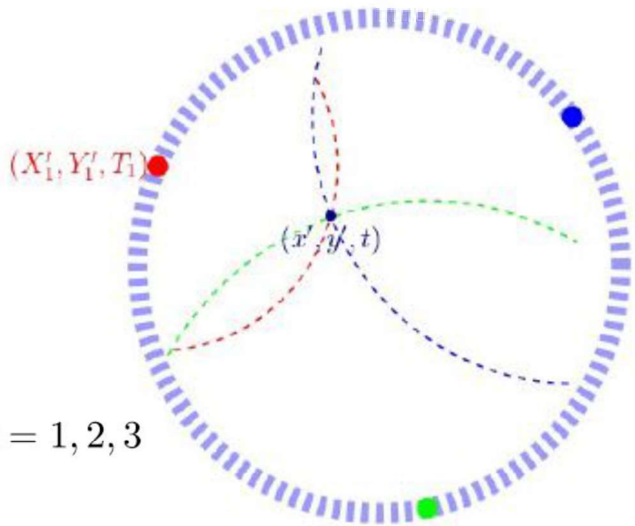
<u>o-Ps→3γ decays reconstruction:</u>

✶ Trilateration-based reconstruction to determine the o-Ps annihilation point



⇓

The decay point **(x',y')** in the decay plane and time **t** is an intersection of 3 circles, each corresponding to a possible origin points of the incident γ



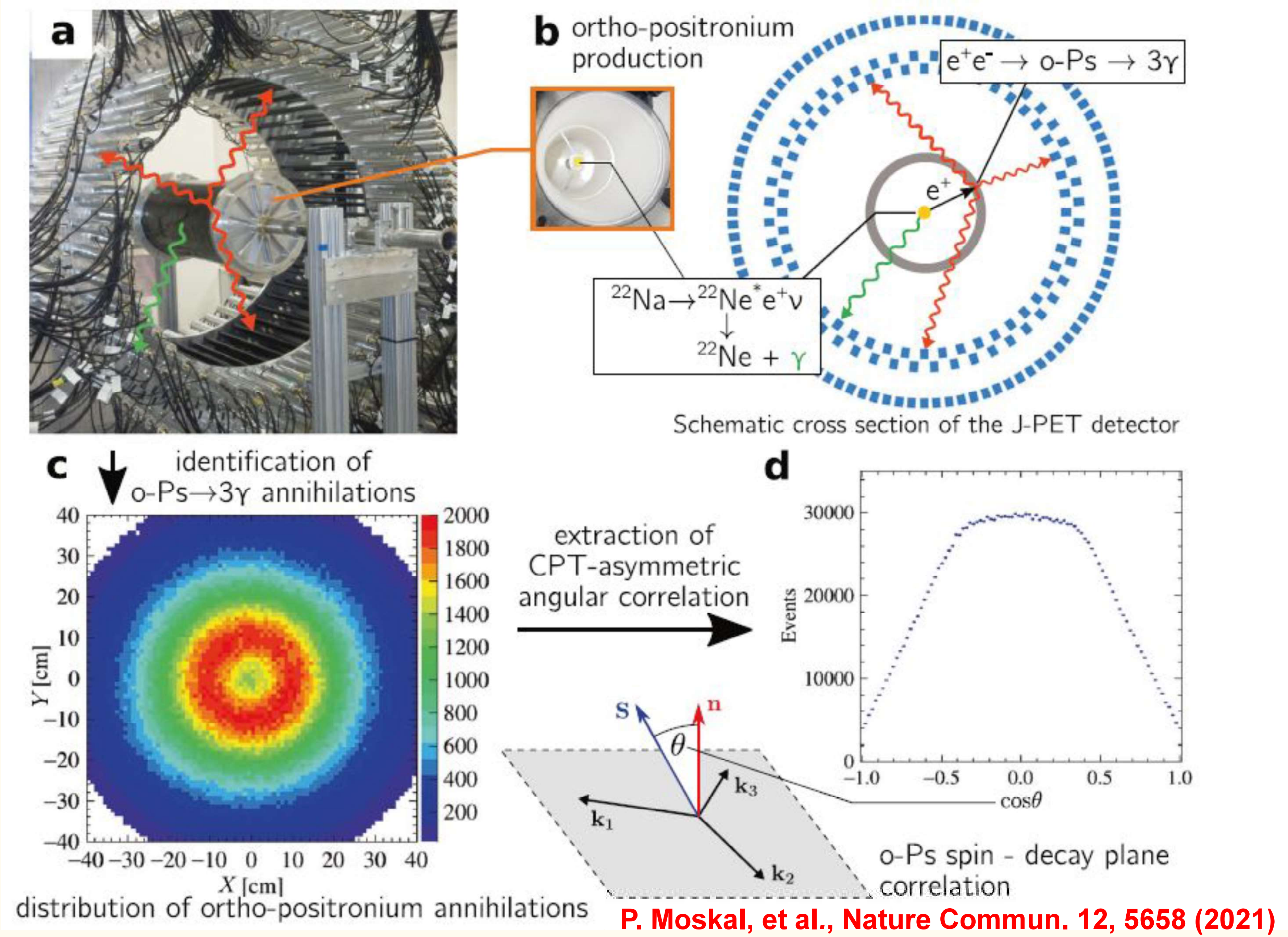
$$(T_i - t)^2 c^2 = (X'_i - x')^2 + (Y'_i - y')^2, \quad i = 1, 2, 3$$

P. Moskal, et al., Nature Commun. 12, 5658 (2021)

[A. Gajos et al., NIM A 819 (2016), 54-59]

Towards <O_{CPT}> determination

26 days of measurement, sodium source activity 10 MBq, 7.3×10^6 event candidates



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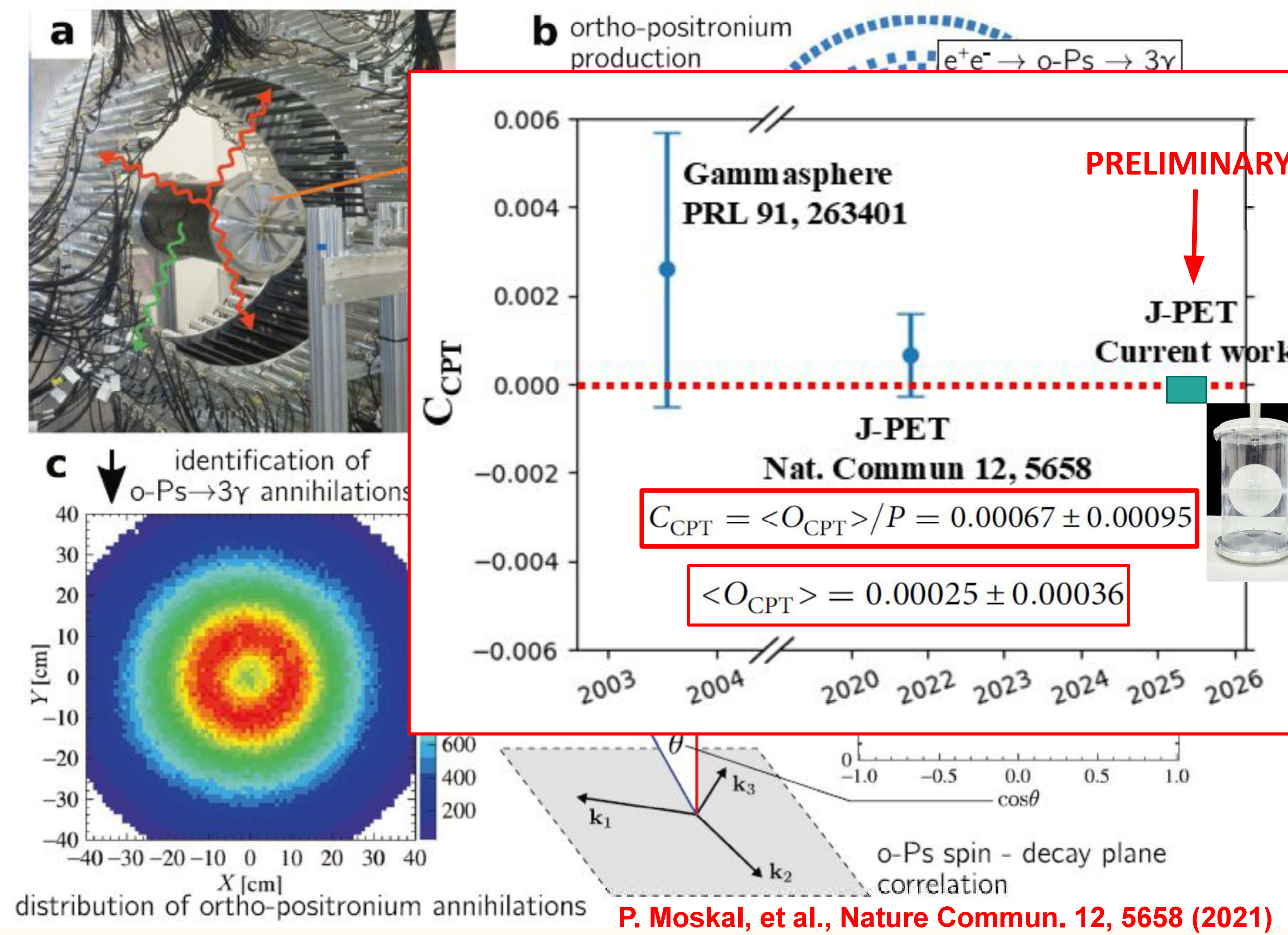
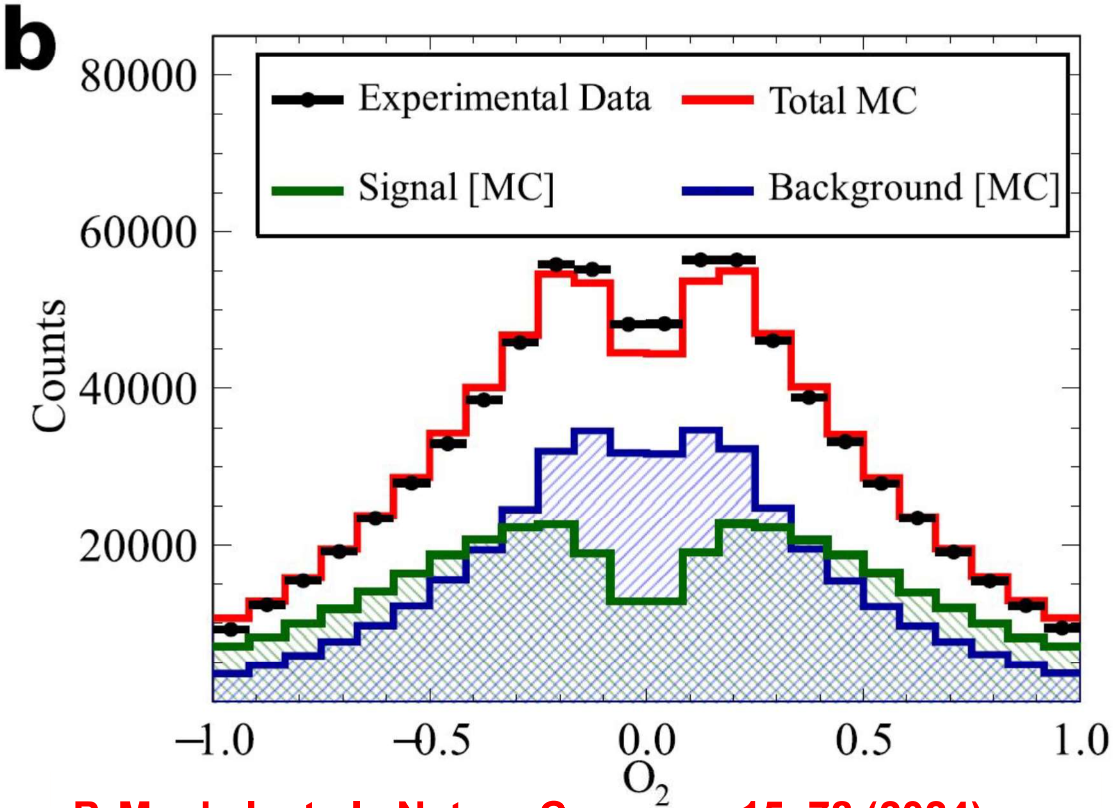


$$C_{CPT} = \langle O_{CPT} \rangle / P = 0.00067 \pm 0.00095$$

$$\langle O_{CPT} \rangle = 0.00025 \pm 0.00036$$

P. Moskal, et al., Nature Commun. 12, 5658 (2021)

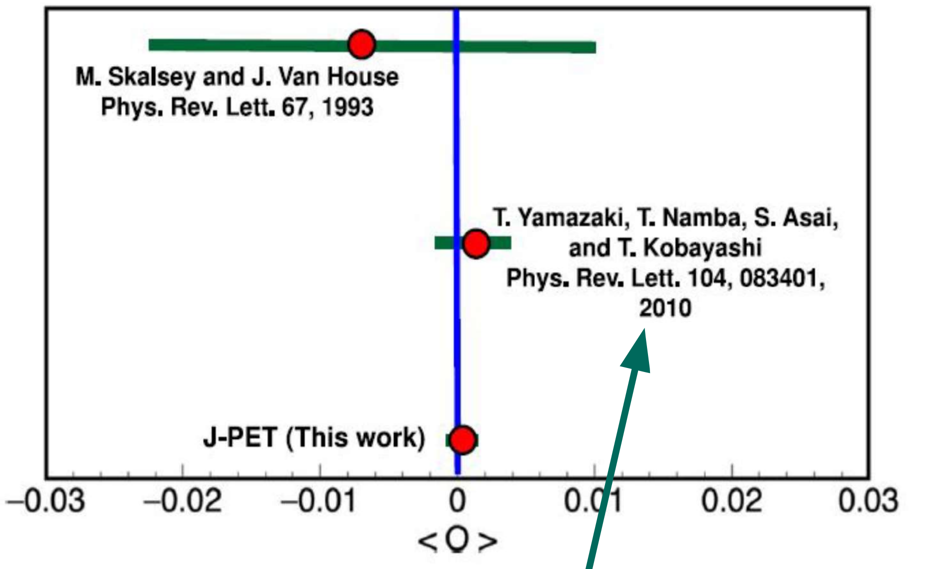
Towards $<O_{CP}>$: determination of the CP observable $O_{CP} = \vec{k}_1 \cdot \vec{\varepsilon}_2 / |\vec{k}_1||\vec{\varepsilon}_2| = cos\theta$



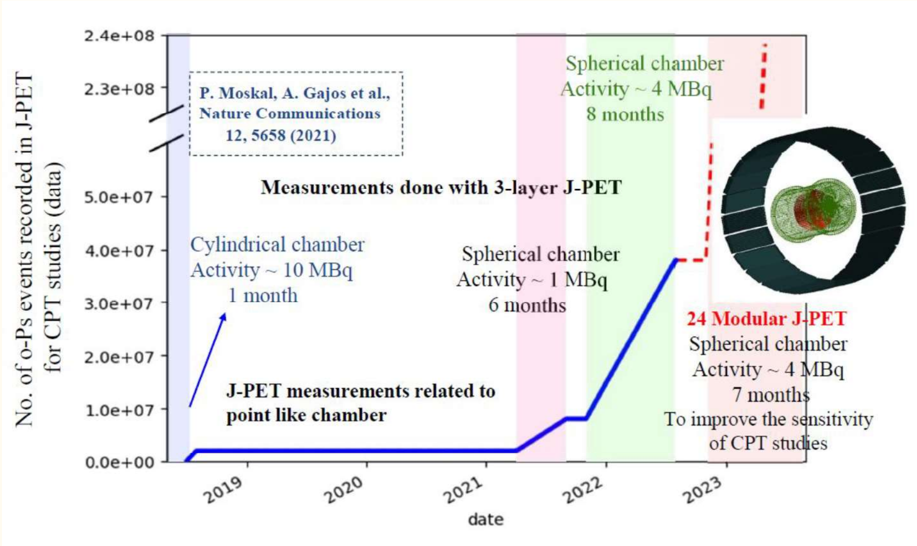
P. Moskal, et al., Nature Commun. 15, 78 (2024)

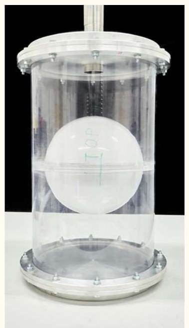
122 days of measurement, four data runs: 2 with ^{22}Na source of 5 MBq activity and 2 with activity of 1 MBq, 7.7×10^5 events

$$< O_{CP} >= 0.0005 \pm 0.0007_{stat.}$$

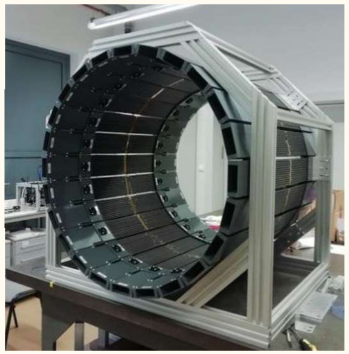


$$< C_{CP}[(\vec{S}\cdot\vec{k}_1)(\vec{S}\cdot(\vec{k}_1 \times \vec{k}_2))] >= 0.0013 \pm 0.0022_{stat.}$$





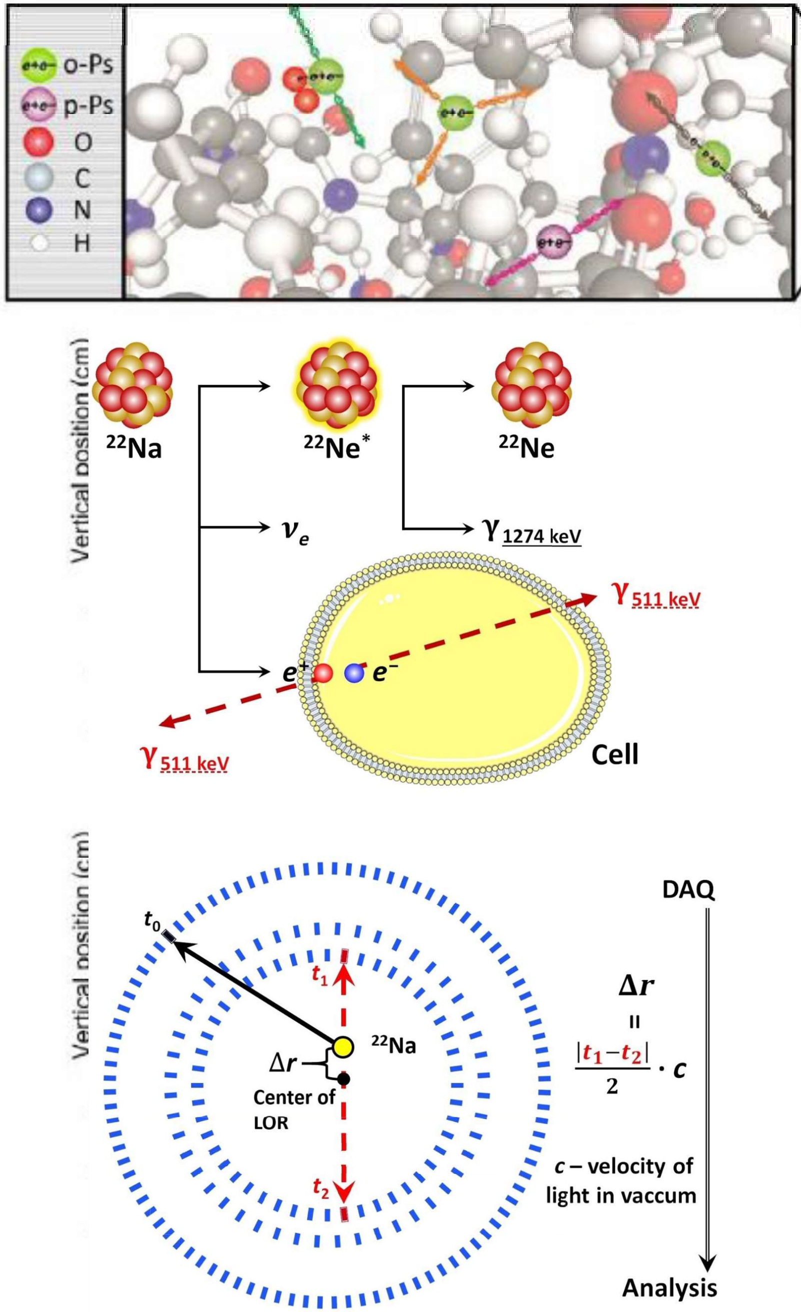
increase positronium formation

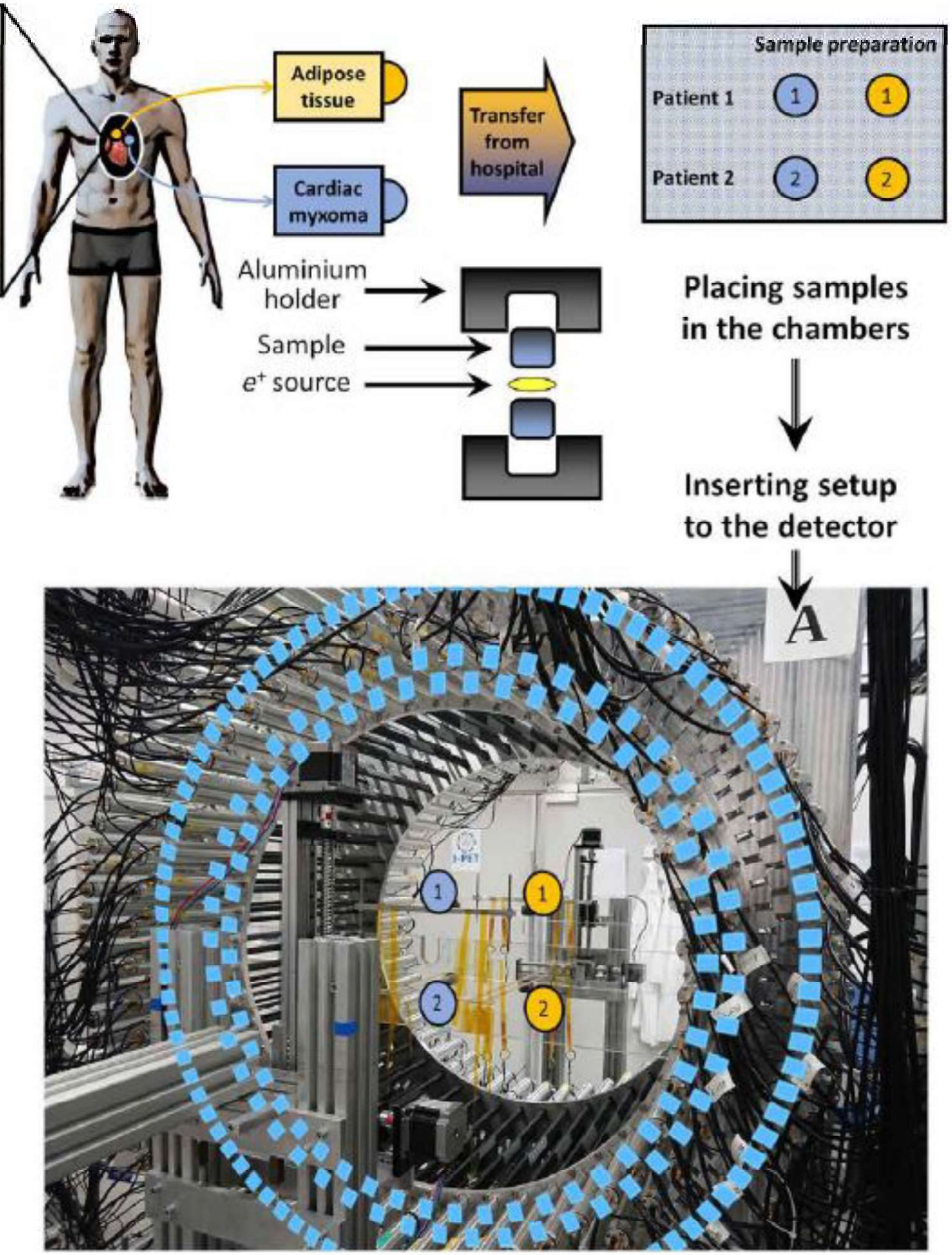


increase of detection efficiency by factor of 60

The first positronium imaging of a phantom built from cardiac myxoma and adipose tissue

ex-vivo studies





P. Moskal, et al., Science Advances 2021; 7 : eabh4394

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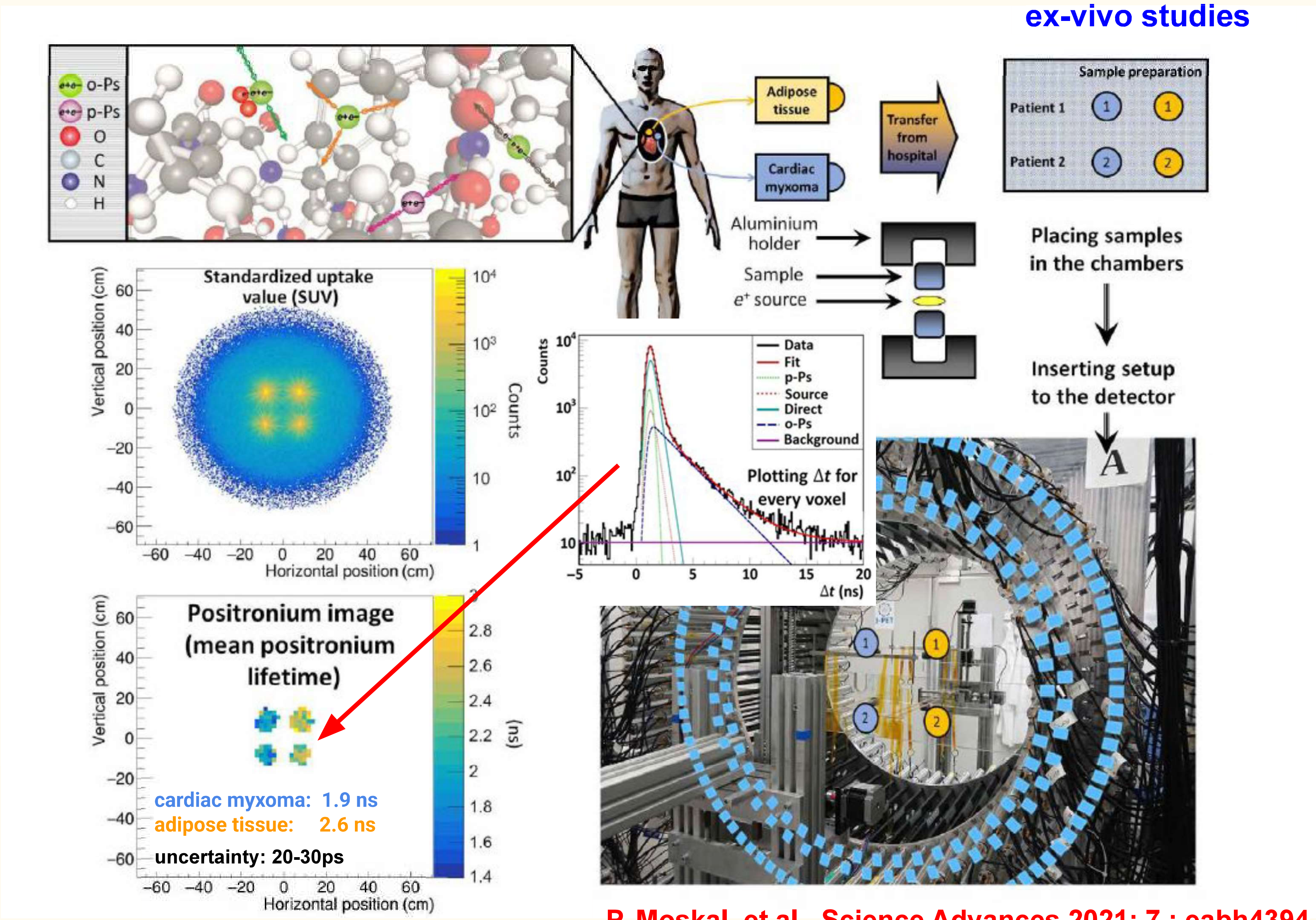
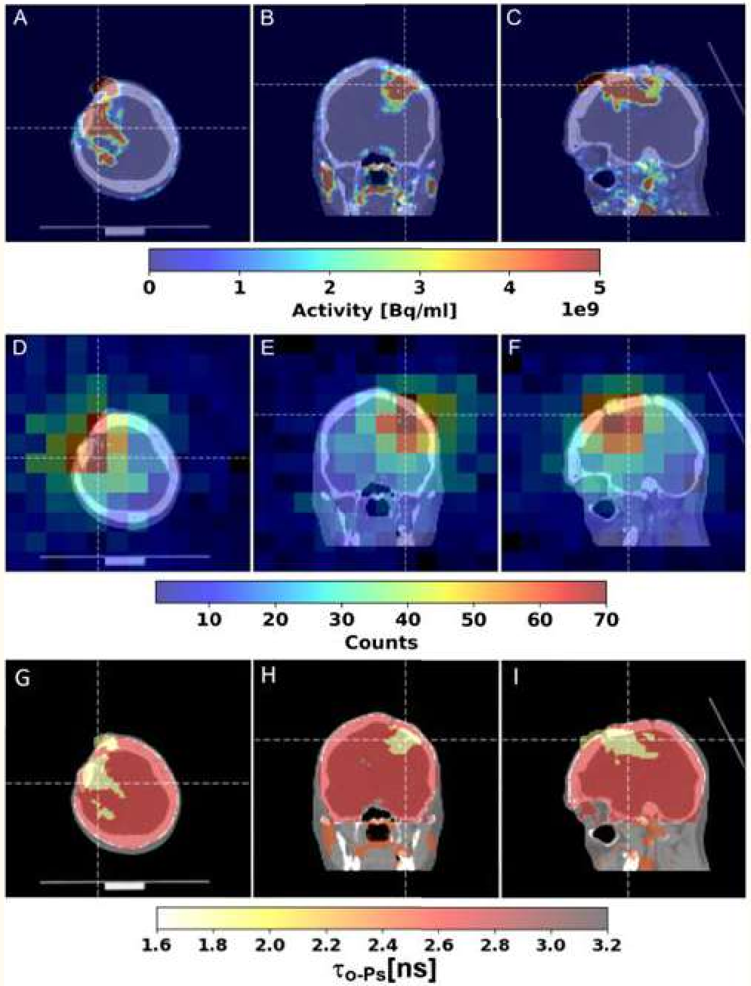
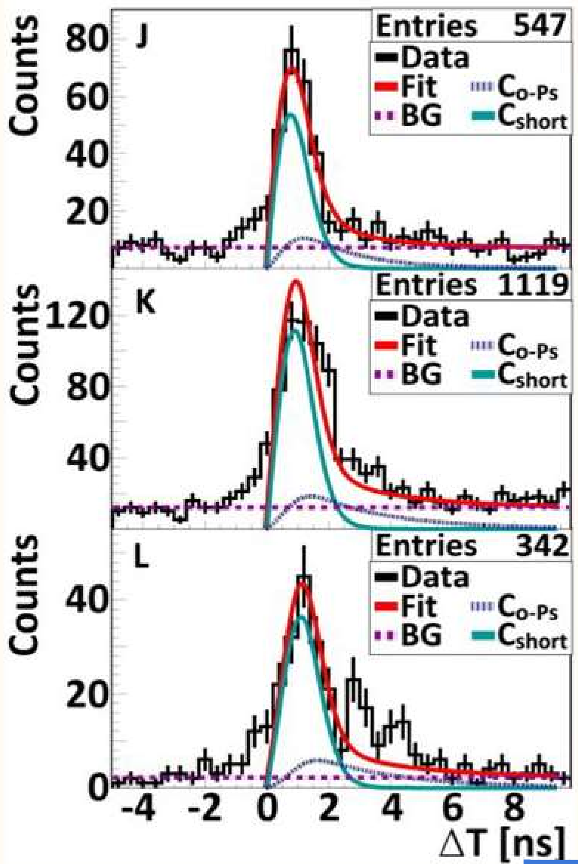


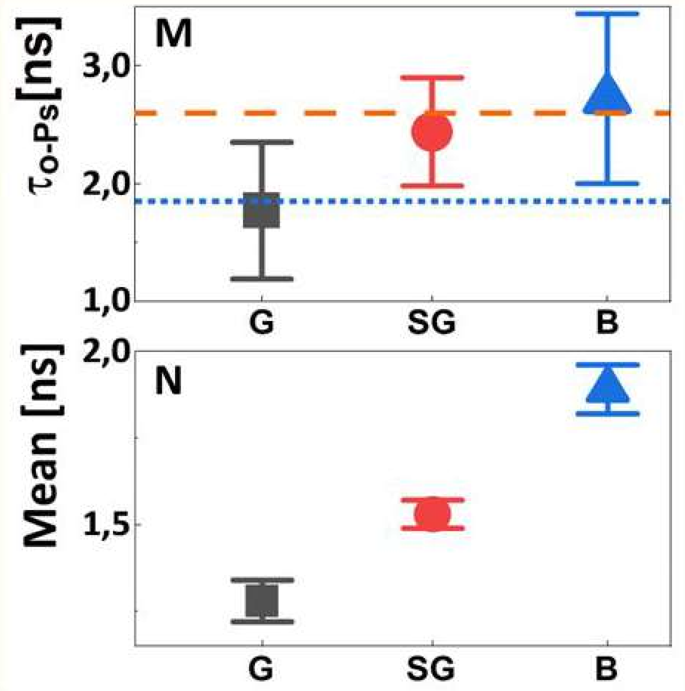
P. Moskal, et al., Science Advances 2021; 7 : eabh4394

Positronium image of the human brain IN VIVO

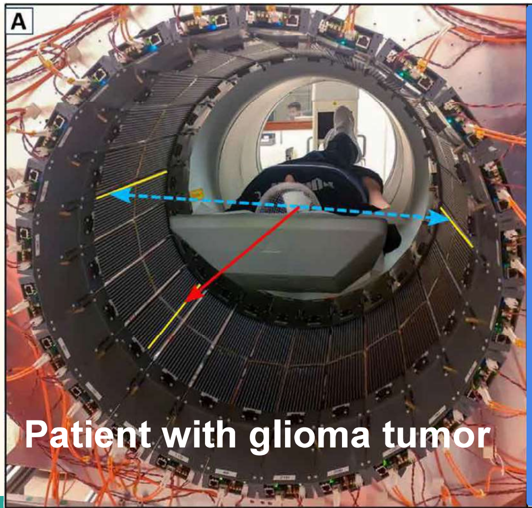


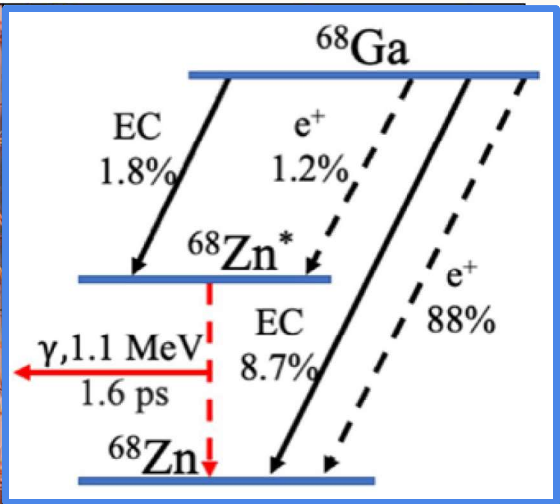


Bioethical Committee consent no. KB/16/2022



tissue	τ_{oPs} [ns]
glioma cancer	1.77 ± 0.58
salivary glands	2.44 ± 0.46
healthy brain tissue	2.72 ± 0.72



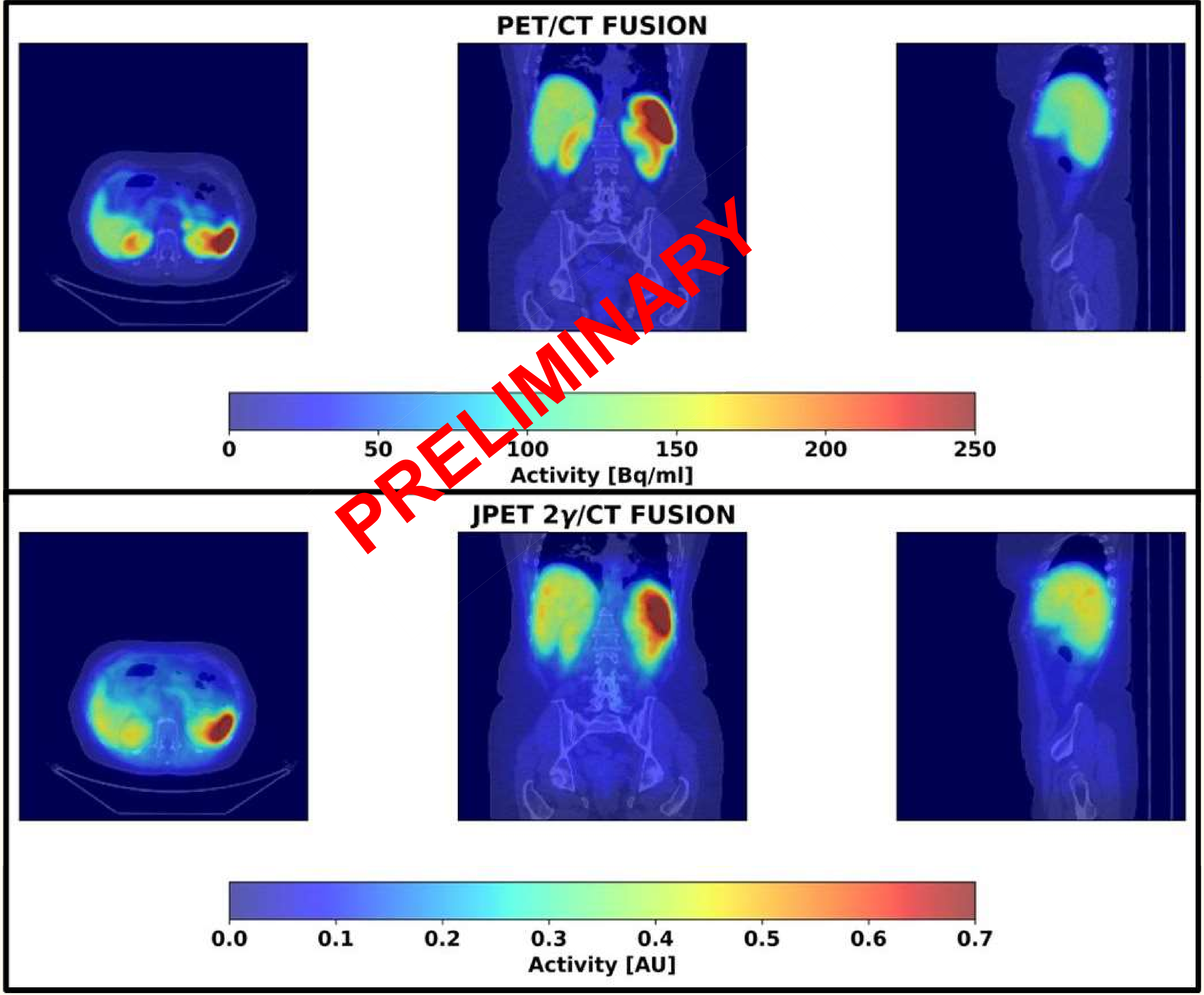


P. Moskal, et al.,
Science Advances 2024; 10 : eadp2840

Measurement campaign - University Hospital in Kraków, 2024

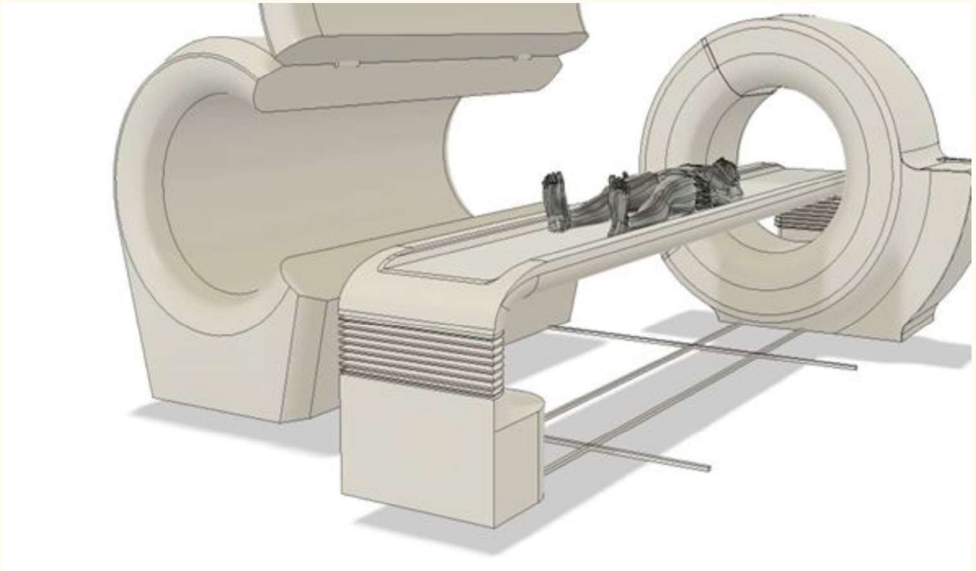
The measurements for patients with liver cancer in University Hospital using J-PET tomograph have been performed in the first half of 2024

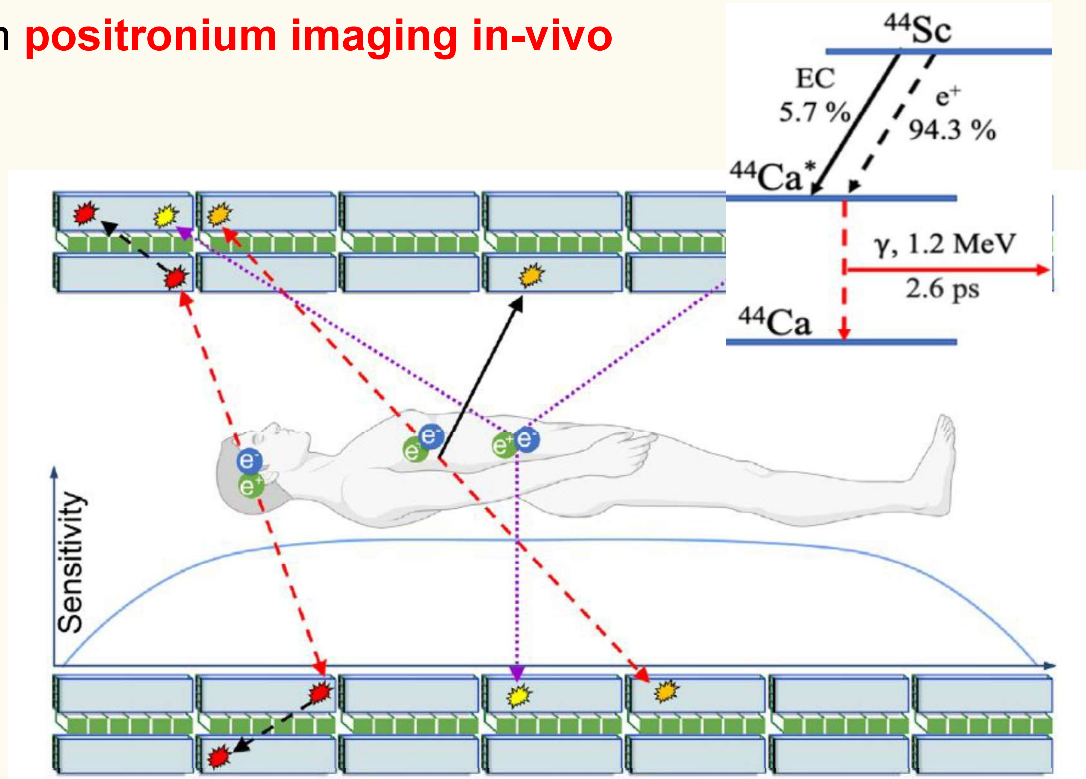
Bioethical Committee consent no. 1072.6120.92.2023


PET/CT FUSION
0
50
100
150
200
250
Activity [Bq/ml]
PRELIMINARY
JPET 2γ/CT FUSION
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
Activity [AU]

Summary and Perspectives

- ➢ With J-PET scanner, we are able to perform exclusive measurement of ortho-positronium (o-Ps) annihilation into 3 photons
  - ○ o-Ps spin event-by-event estimation
  - ○ o-Ps→3γ decays reconstruction including determination of the annihilation point in an extensive-size medium
  - ○ determination of polarization of annihilation γ quanta
- ➢ **Sub-permil precision of the CPT and CP tests reached with the first J-PET measurements: over factor of 3 better** than the previous results
- ➢ J-PET aims at the sensitivity of the CP and CPT symmetry tests at the level of 10^{-5} with the pending improvements to the setup
- ➢ With J-PET scanner, we are able to perform **positronium imaging in-vivo**
- ➢ **Main aim: TB-JPET construction**





TB-J-PET + 44Sc -> positronium imaging with housands of times greater sensitivity